A survey on gas leak detection and localization techniques

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Abstract

Gas leaks can cause major incidents resulting in both human injuries and financial losses. To avoid such situations, a considerable amount of effort has been devoted to the development of reliable techniques for detecting gas leakage. As knowing about the existence of a leak is not always enough to launch a corrective action, some of the leak detection techniques were designed to allow the possibility of locating the leak. The main purpose of this paper is to identify the state-of-the-art in leak detection and localization methods. Additionally we evaluate the capabilities of these techniques in order to identify the advantages and disadvantages of using each leak detection solution.

Keywords: gas leak, leak detection, leak localization, pipeline

1. Introduction

The worldwide natural gas transport and distribution network is a complex and continuously expanding one. According to the study presented in (TRB, 2004), pipelines, as a means of transport, are the safest but this does not mean they are risk-free. Therefore, assuring the reliability of the gas pipeline infrastructure has become a critical need for the energy sector. The main threat considered, when looking for means of providing the reliability of the pipeline network, is the occurrence of leaks.

Regardless of their size, pipeline leaks are a major concern due to the considerable effects that they might have. These effects extend beyond the costs involved by downtime and repair expenses, and can include human injuries as well as environmental disasters. The main causes of gas pipeline accidents are (EGIG, 2008): external interference, corrosion, construction defects, material failure and ground movement.

To counteract the disastrous effects of gas leaks, considerable effort has been invested, during the last decades, in designing gas leak detection techniques. However, revealing the presence of a gas leak is not sufficient in order to define an efficient counteracting measure. Before deciding on a set of corrective actions, other information has to be known such as: the location of the leak, its size, etc. These subjects were also in the focus of research done in the field of pipeline reliability assurance.

The occurrence of gas leak-related incidents was studied by several organizations which published statistics on the reported incidents. One of these studies, made on the sub-sea pipeline systems (SLR, 2009), states that, between 1996 and 2006, a number of 80 pipeline rupture incidents were reported in the Gulf of Mexico and Pacific areas. Based on data gathered in this report, the calculated probability of a catastrophic incident, for the specified area, is 0.43 incidents per year. Another survey (Konersmann et al., 2009), which focuses on the risks of pipeline transportation, covers incidents that occurred in Europe and on the American continent presenting the main causes of pipeline failure. According to this report, in the province of Alberta/Canada alone, there have been 1326 reported gas leaks in the 2001-2005 period. A different report shows that large pipelines (i.e. with a length of 800 miles or more) can expect at least one reportable leak-related incident per year (ADEC, 1999). This evidence indicates that the risk of incidents caused by

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Preprint version of the article accepted in Journal of Loss Prevention in the Process Industries

gas leaks is substantial despite the great variety of leak detection methods available and serves as motivation of our work.

The main purpose of this paper is to identify the state-of-the-art in gas leak detection techniques and to present localizing capabilities, as well as other important features, for each of the studied methods. We achieve this by performing an extensive survey of the literature in the field, covering results from academia as well as industry reports.

A number of reviews on the subject of gas leak detection techniques were done in the past either as part of research papers/technical reports on a certain leak detection method and other gas related subjects (Zhang, 1997; Matos et al., 2006; Folga, 2007; Liu et al., 2008; Batzias et al., 2011) or as a result of research dedicated to this specific purpose (Jolly et al., 1992; Stafford and Williams, 1996; ADEC, 1999; Wang et al., 2001; Scott and Barrufet, 2003; Sivathanu, 2003; Geiger et al., 2003; Loth et al., 2003; USDT, 2007; Turkowski et al., 2007; El-Shiekh, 2010). Although they provide a good overview on existent leak detection techniques, these surveys are either succinct, omitting several leak detection methods or, in some cases, not of a recent date.

In order to decide which leak detection technique is more suitable for a given setting, a comparative performance analysis is necessary. For this we compare the studied methods by a set of common features using performance reports from literature. As a conclusion, and apparently future trend, a hybrid approach combining different detection methods to achieve the required system performance would be the best choice.

This paper is organized as follows. The analyzed methods are first classified, in section 2, by a number of different criteria ranging from the measured physical quantity to the amount of human intervention required. Each of the identified methods are then described in sections 3 through 5 followed by a compared performance analysis in section 6. Finally, the conclusion of this work is presented in section 7.

2. Classifying leak detection technologies

For the purpose of this survey we first look at classifying the available leak detection techniques. Several criteria are considered for classification, some of which are: the amount of human intervention needed, the physical quantity measured and the technical nature of the methods.

If the degree of intervention needed from a human by each detection method is chosen to classify these methods, we distinguish three categories:

- **automated detection** - complete monitoring systems that, can report the detection of a gas leak without the need of a human operator, once they are installed (e.g. fiber optic or cable sensors).
- **semi-automated detection** - solutions that need a certain amount of input or help in performing some tasks (e.g. statistical or digital signal processing methods)
- **manual detection** - systems and devices that can only be directly operated by a person (e.g. thermal imagers or LIDAR devices).

Most detection techniques rely on the measurement of a certain physical quantity or the manifestation of a certain physical phenomenon. This can be used as a rule for classification as we have several common used physical parameters and phenomena: acoustics, flow rate, pressure, gas sampling, optics and sometimes a mix of these. An example is available in relation to the optical detection methods. Because of the great variety of these detection solutions, leak finding technologies are sometimes classified into optical and non-optical methods (Sivathanu, 2003; Batzias et al., 2011).

Some authors see the technology as fitting into two great categories **direct** and **indirect** or inferential methods (Folga, 2007; Liu et al., 2008). The direct detection is made by patrolling along the pipelines using either visual inspection or handheld devices for measuring gas emanations. Thanks to the technological advancements it is now common to use helicopter- or airplane-mounted optical imaging devices especially for very long pipelines (Liu et al., 2008). Indirect or inferential methods detect leaks by measuring the change of certain pipe parameters such as flow rate and pressure.

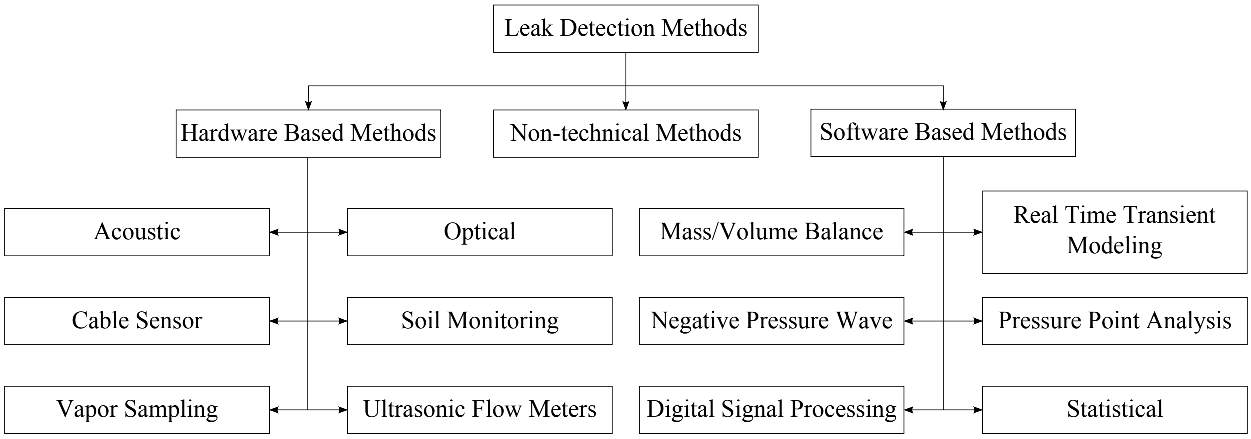

Figure 1: Classification of gas leak detection techniques based on their technical nature

The most common way of classifying leak detection methods is based on their technical nature (Scott and Barrufet, 2003). We can thus distinguish two main categories of methods: **hardware based methods** and **software based methods**. These two categories are sometimes mentioned as externally or internally based leak detection systems (Geiger et al., 2003). Although not often presented in recent literature as a separate category, there is a third class that covers the so-called **biological methods** (Zhang, 1997). We will refer to these methods as non-technical. Figure 1 illustrates these main categories and the different methods associated with each of them. This classification is similar to the one presented in the previous paragraph with the remark that indirect or inferential methods overlap with the software based methods while the direct methods cover both hardware methods and non-technical methods.

Non-technical leak detection methods are the ones that do not make use of any device and rely only on the natural senses (i.e. hearing, smelling and seeing) of humans and/or animals.

Hardware based methods rely mainly on the usage of special sensing devices in the detection of gas leaks. Depending on the type of sensors and equipment used for detection, these hardware methods can be further classified as: *acoustic*, *optical*, *cable sensor*, *soil monitoring*, *ultrasonic flow meters* and *vapor sampling*.

Software based methods, as the name states, have software programs at their core. The implemented algorithms continuously monitor the state of pressure, temperature, flow rate or other pipeline parameters and can infer, based on the evolution of these quantities, if a leak has occurred. The software methods can use different approaches to detect leaks: *mass/volume balance*, *real time transient modeling*, *acoustic/negative pressure wave*, *pressure point analysis*, *statistics* or *digital signal processing*.

In the next sections, we will go through all these techniques using the classification in Figure 1 as a template for organizing this survey. The functioning principle of each method is presented along with the advantages and disadvantages of using it.

3. Non-technical methods

As stated, these methods involve personnel patrolling along the pipelines looking for visual effects of a gas leak, smelling substances that might be released through a leak or listening to specific sounds that can be made by gas as it leaks out. Sometimes trained dogs are used as they are more sensitive to the smell of certain gases (Quaife and Acker, 1993; Kennedy, 2005). The sensitivity of dogs, depending on the target compound, has been found to be in the 10 parts-per-billion (ppb) - 500 parts-per-trillion (ppt) range, in laboratory conditions (Johnston, 1999). However, using canines to detect leaks has the disadvantage that they can not be effective for periods longer than 30 to 120 minutes of continuous searching (Garner et al., 2001). Additionally, the accuracy of this approach can be affected by fatigue and the interpretation given by the handler to the canine response. These on-site inspections are required in some countries such as the USA as a regulation for hazardous substance pipelines operators (USDT, 2007).

Soap bubble screening, which is a low-cost method for locating smaller leaks (Liu et al., 2008), can also be included in this category. It involves spraying a soap solution on different components of the pipeline or on suspicious surfaces on the pipe. Usually soap screening is mainly applied to valves and piping joints as these are gas leak prone places. This method is rapid and has a small cost, thus it would be helpful as a part of the routine inspection procedures.

The use of this type of methods has the advantage that it requires no special equipment and that they result in the immediate localization of the leak upon detection. Unfortunately there are also some downsides for using it. For instance the detection time depends on the frequency of these inspections which is usually reduced (e.g. the USA regulation states that these inspections should be done at least once every three weeks). The detection of a leak greatly depends on the experience and meticulousness of the employed personnel. Another disadvantage is that this method can only be applied to pipelines that are accessible to personnel ruling out its application in the case of buried pipes.

4. Hardware based methods

4.1. Acoustic methods

Escaping gas generates an acoustic signal as it flows through a breach in the pipe. Thus, this signal could be used to determine that a leak has occurred. To record the internal pipeline noise, acoustic sensors have to be used. They can be integrated in handheld detection devices employed by personnel patrolling the pipeline or in intelligent pigs that travel through the pipeline inspecting it (Furness and van Reet, 2009). Continuous monitoring is also done by installing acoustic sensors outside the pipeline at certain distance from one another (Brodetsky and Savic, 1993). The distance between two acoustical sensors has to be adapted based on the sensitivity of the acoustic sensor and allocated budget. Placing sensors too far from each other will increase the risk of undetected leaks while installing them too close will lead to an increased system cost. Several types of sensors were used to detect sounds produced by gas leaking out. They range from acoustic sensors and accelerometers to microphones and dynamic pressure transducers all of which are detailed in (Loth et al., 2003).

Acoustic leak detection techniques have been studied since the 1930's and their evolution is presented in a comprehensive survey on the subject (Loth et al., 2003). Rocha (Rocha, 1989) used pressure sensors to record the appearance of acoustic pressure waves caused by leaks, while Brodetsky and Savic developed a system that requires permanent monitoring units along the pipeline using a k nearest neighbor classifier to distinguish leaks from background noise (Brodetsky and Savic, 1993). Some methods involve the measurement of two acoustic signals on each end of a pipe segment. Based on these measurements, the leak can be detected using a time-frequency technique (Kim and Lee, 2009) or the low frequency impulse method (Loth et al., 2003). A more recent experimental study focused on distinguishing between signals made by leaks and background noises using time-frequency analysis and adapted the leak location formula to increase accuracy (Meng et al., 2011).

In what regards the advantages of using this technique, we can mention the fact that continuous mode operation is feasible and that the system can be automated. Acoustic methods can also help in determining the location of the leak and estimating its size. This technique could be used on new as well as on existing pipelines. When in continuous monitoring mode the system can respond in real-time. As a disadvantage high background or flow noise conditions may mask the actual leak signal (e.g. noise from vehicles passing by, valve or pump noise). As a financial downside, the cost of installing numerous sensors needed for long pipelines is high.

4.2. Optical methods

Optical methods used for leak detection can be divided in two categories (Reichardt et al., 2002): passive or active. Active methods require illuminating the scanned area using a radiation source while passive methods do not require a source and rely only on background radiation or the radiation emitted by the gas.

Some general benefits of using optical methods are their portability, remote detection and leak locating capabilities. A common approach is to survey the natural gas pipeline networks using aircraft-mounted optical devices for leak detection (ITT Corporation, 2009). The resulting map offers an overview of the entire network and reveals the locations of existing leaks faster than they would be found by a ground patrol with hand-held devices. The sole exception in regards to portability comes from fiber optic sensing.

Active methods. The absorption or scattering of the emitted radiation caused by natural gas molecules is monitored and if significant absorption or scattering is detected above a pipeline, then a leak is presumed to exist. Several active methods for optical detection of natural gas leaks were studied such as LIDAR (LIght Detection And Ranging) systems, diode laser absorption, millimeter wave radar systems, backscatter imaging, broad band absorption and optical fiber.

LIDAR systems (Minato et al., 1999; Ikuta et al., 1999) use a pulsed laser to illuminate the scene and a detector to monitor the absorption of the laser energy along the length of a path. This is a sensitive technique that can be used for remote monitoring. However, the high price of the pulsed lasers and short system lifetime come as a downside.

Diode laser absorption (Iseki et al., 2000) is similar in technology to LIDAR systems but with a significant difference. Instead of the expensive pulsed lasers, the illumination is given by diode lasers. This method is suitable both for close-range handheld detectors and high altitude aerial detection (Wainner et al., 2007). One disadvantage of these systems is the possibility of generating false alarms.

Millimeter wave radar systems (Gopalsami and Raptis, 2001) are based on the radar signature of the area above the gas pipelines. Gases such as methane are lighter than air and this difference in density can produce a specific radar signature that can be evaluated in order to detect potential leaks. This method is an effective one but also expensive.

Backscatter imaging (Kulp et al., 1993; Kasai et al., 2011) is another expensive technique which involves using a carbon-dioxide laser for illuminating the scene. As the natural gas scatters the laser light, the scattering signature is captured using an infrared camera. The patterns revealed by the camera can then show if a gas leak is present.

In broad band absorption systems (Spaeth and O'Brien, 2003) low cost lamps are used to provide the source. To reduce the probability of false alarms, multiple wavelengths are used for monitoring. This system can provide long range detection but is still prone to false alarms.

Optical fiber can be used to monitor a series of physical and chemical properties (Tapanes, 2001). Changes in temperature as a result of gas escaping from the pipe will be signaled by the sensing fiber optic cable that has to be located in close proximity to the pipe (Tanimola and Hill, 2009). The optical properties of fiber optic are affected by the presence of hydrocarbons thus providing another means of detecting gas leaks. These changes in the transmission characteristics are recorded with the use of lasers and optical detectors. The leak location and leaked gas concentration can also be detected using fiber optic sensing. One significant advantage of using fiber optic is that it is immune to electromagnetic interference. Several downsides were also reported for using this technique such as high costs and the stability over time of the fiber chemical coating. Furthermore, applying this method to already existing pipeline systems may be difficult as it would require, in some cases, digging up buried pipes to place the fiber optic cable close to the pipe.

Passive methods. As already stated the main difference between passive and active monitoring is that passive monitoring does not require a radiation source. This is an advantage as the lack of a source means some cost savings. However, this lack has to be compensated with more performant detectors and imagers which are expensive. There are several types of passive leak detection systems: thermal imaging, multi-spectral imaging and gas filter correlation radiometry.

Thermal imaging (Weil, 1993) utilizes the differences in temperature between the leaked gas and the surrounding environment to detect leaks. This method can be used from ground and aerial vehicles, and was also successfully installed on autonomous robots (Kroll et al., 2009). The thermal imagers required to detect small differences in temperature are however expensive. An additional disadvantage is that the leak can't be detected if the escaping gas has the same temperature as the surrounding environment.

Multi-spectral or multi-wavelength imaging (Bennett et al., 1995; Gittins and Marinelli, 1998; Cosofret et al., 2004) can be used in absorption mode or in emission mode. Using this technique in emission mode can lead to the detection of leaks if the temperature of the escaping gas is much higher than the surrounding air temperature. For multi-wavelength absorption imaging, the absorption of background radiation is recorded at multiple wavelengths to generate a map of the gas concentration. This can be achieved even if there is no significant difference between the temperature of the leaked gas and the environment. This technique has a negligible chance of generating false alarms and can be used in remote detection without constant supervision. However, the sensitive imagers needed for employing this kind of detection are very expensive.

Gas Filter Correlation Radiometry (GFCR) (Tolton et al., 2008) uses a sample of the target gas as a spectral filter. Incoming radiation goes through a narrow band-pass filter after which the beam is split along two paths: one that has a cell filled with the gas of interest (called correlation cell) and another path that has an empty cell. The spectral filter comprised of the correlation cell is used to remove the energy from the incoming beam at wavelengths corresponding to the absorption lines of the gas. Radiant fluxes from the two paths are measured using infrared detectors and used to decide if a gas leak is present. GFCR instruments like the realSens^{TM}(Synodon Inc., 2009) are mounted on aircrafts such as a helicopter and can locate leaks from an altitude of 300 meters.

4.3. Cable sensor

Optical fiber cables, which were already presented, are not the only cable detection technique available. Electrical cable sensors have also been used for gas leak detection. The cables are built using materials that react when in contact to certain substances. This reaction changes cable properties such as resistance or capacitance which can be monitored to sense the appearance of a leak. Sandberg et al. (Sandberg et al., 1989) used a sensing cable sensitive to hydrocarbons in a system that could detect and locate leaks with an accuracy of about 20 meters.

Some cables contain two circuit loops (USEPA, 2004). One circuit will be connected to a power supply and the other one to an alarm. When the two circuits come into contact the alarm will be signaled. The short can be produced using several mechanisms, depending on the cable used. Direct wire contact can occur when the material separating the wires degrades, in the presence of leaked gas, allowing them to touch. The same effect is achieved when using a coating material that swells, once in contact with the gas, forcing the two wires together.

This leak detection technique gives a reasonably fast response and is more sensitive than some computational methods. However, the costs of implementing such a system are quite high. Other notable disadvantages are the difficulty of retrofitting this to existing pipelines and the inability of estimating the leak size.

4.4. Soil monitoring

Soil monitoring involves inoculating the gas pipeline with an amount of tracer compound (Lowry et al., 2000). This tracer chemical, a non-hazardous and highly volatile gas, will exit the pipe in the exact place of the leak (if this has occurred). To detect a leak, instrumentation has to be used to monitor the surface above the pipeline by dragging devices along it (Praxair Technology Inc., 2007) or through probes installed in the soil near to the pipelines. The samples collected are then analyzed using a gas chromatograph (Thompson and Golding, 1993).

The very low false alarm rate and high sensitivity are some of the advantages of using soil monitoring for leak detection. The method is quite expensive because trace chemicals have to be continuously added to the pipe during the detection process. The name of the method comes from another disadvantage, which is that it cannot be used for exposed pipelines.

4.5. Vapor sampling

Leaks can be detected also by sampling hydrocarbon vapors in the vicinity of the pipeline. This can be done either through a vapor monitoring system which involves a sensor tube buried along the pipeline (Sperl, 1991), either by using mobile detectors carried by personnel or mounted on ROVs (remotely operated vehicles).

The remote monitoring system uses a sensor tube buried in parallel to the pipeline. The tube is permeable to the target gas so that in the event of a leak, some of the escaped gas will diffuse into the tube. In order to analyze the content of the tube, a pump is used to periodically push the content of the tube past a monitoring unit. The concentration profile will not be affected by the pumping action. Sensors in the detector unit will detect the gas concentration at a certain point in the examined air column, determining the size of the leak based on this concentration. To determine the location of the leak, a test gas is injected in the tube before the start of each pumping action. In this way, when the test gas is sensed by the detector unit it means that all the column was checked. The travel time of the gas from a leak spot on the pipeline, relative to the overall travel time, is used to find the location of the leak. This method has a slower response time than other monitoring methods and it is typically used for short pipelines. The LEOS leak detection system (Bryce et al., 2002) is supposed to work for methane gas pipelines up to 50 kilometers in length. According to the same source, this system has a detection threshold of 0.05% for gas leaks. This method is not applicable to above ground or high depth pipelines and the costs of employing it are extremely high.

Handheld or vehicle mounted gas sampling detectors are built using a great variety of sensors. The different types of gas sensors are covered in (Comini et al., 2009) and some recent advances in this field are presented in (Ren and Pearton, 2011). This approach can give better results than non-technical detection especially for very small leaks but its success greatly depends on the frequency of the patrols.

4.6. Ultrasonic flow meters

Systems based on ultrasonic flow meters can also be used for gas leak detection. Such systems were designed by Controlotron (Controlotron Corporation, 2005, 2006) and then overtaken by Siemens Industry Automation division (Siemens Industry Inc., 2011a). The system offered by this company works by considering that the pipeline is comprised of a series of segments. Each segment is bounded by two so-called Site Stations which consist of a clamp-on flow meter, a temperature sensor, and a processing unit. Each Site Station will measure or compute volumetric flow rates, gas and ambient air temperature, sonic propagation velocity and site diagnostic conditions. All data obtained on Site Stations are collected by a Master Station which computes the volume balance by comparing the difference in the gas volume entering and leaving each pipeline segment. Short integration periods show large leaks very quickly while longer integration periods detect smaller leaks (Bloom, 2004; Siemens Industry Inc., 2011b).

This technology can locate the leak with an accuracy of 150 meters. Another advantage is offered by the non-intrusive character of the electronic devices utilized. On the downside, retrofitting to buried pipelines would be difficult.

5. Software based methods

5.1. Mass/Volume Balance

The mass or volume balance leak detection technique is based on the principle of mass conservation. An imbalance between the input and output gas mass or volume can reveal the existence of a leak (Parry et al., 1992; Liou, 1996). The volume of gas exiting a section of the pipeline is subtracted from the volume of gas entering this section and if the difference is above a certain threshold, a leak alarm is given. The mass or volume can be computed using the readings of some commonly used process variables: flow rate, pressure and temperature. A detailed description of the theory behind this method and implementation issues are presented in (Liu, 2008).

MassPack^{TM}(EFA Technologies Inc., 2011a) is one of the mass balance based leak detection systems available. It is offered by EFA Technologies Inc. as part of the LEAKNET^{TM}package for leak detection and relies on accumulating differences between inflow and outflow measurements. The sensitivity of MassPack^{TM}relies on meter accuracy but it is also tolerant to low performance meters.

The mass balance approach was also used in conjunction with probabilistic methods for leak detection (Rougier, 2005). However, probabilistic methods need a considerable amount of computational power.

The performance of this method mainly depends on the size of the leak, how frequently is the balance calculated and the accuracy of measuring instruments. It can be easily installed in existing pipelines as it relies on instrumentation that is available on all pipelines and it is easy to learn and use. The relatively low cost is another advantage of this method. Balancing techniques are however limited in what regards leak detection during transient or shut in and slack line conditions. If small leaks occur, it takes a long time to detect them. For example, a 1% leak needs aproximately 60 minutes to be detected (Doorhy, 2011). This method cannot be used for locating the leak and it is prone to false alarms during transient states unless thresholds are adapted.

5.2. Real Time Transient Modeling

Some leak detection techniques work on pipe flow models built using equations like: conservation of mass, conservation of momentum, conservation of energy and the equation of state for the fluid. The difference between the measured value and the predicted value of the flow is used to determine the presence of leaks. Flow, pressure and temperature measurements are required by this technique. Noise levels and transient events are continuously monitored in order to minimize false alarms.

Billman and Isermann (Billmann and Isermann, 1987) are among the first to use this approach. They designed an observer with friction adaptation which, in the event of a leak, will generate a different output than the one obtained from measurements, thus leading to the detection of the leak. Another proposal uses a linearized, discretized pipe flow model on a N-node grid and a bank of observers (Verde and Visairo, 2001; Verde, 2001). The observers were built so that in case of a leak, all but one will react. The position of the non responsive observer leads to the localization of the leak while the outputs of the other observers can be used to quantify the leak. Aamo et al. designed (Aamo et al., 2006) and later improved (Hauge et al., 2007) a detection system that employs an adaptive Luenberger-type observer based on a set of two coupled one dimensional first order nonlinear hyperbolic partial differential equations.

This method can detect small leaks (less than 1 percent of flow (Scott and Barrufet, 2003)) but has the disadvantage of being very expensive as it requires extensive instrumentation for collecting data in real-time. The models employed are complex and they require a trained user.

5.3. Negative Pressure Wave

A leak occurring in a pipeline is associated with a sudden pressure drop, at the location of the leak, which is propagated as a wave both upstream and downstream. This wave is called a rarefaction or negative pressure wave and can be recorded using pressure transducers installed at both ends of each pipe segment (Silva et al., 1996). The leak detection algorithm has to interpret the readings obtained from the pressure transducers and decide if a leak is present. Different approaches, including support vector machine learning (Chen et al., 2004), were used for this purpose. The location of the leak can be identified using the time difference between the moments at which the two pressure transducers from the pipe ends sense the negative pressure wave. If the leak is closer to one end of the pipe, then the transducer from this end will be the first to receive the pulse and the amount of time needed to receive the pulse at the other end can be used to detect the leak location with good precision. Negative pressure wave based leak detection systems, such as ATMOS Wave (Souza de Joode and Hoffman, 2011; Twomey, 2011), can also estimate the size of the leak.

Another way of using pressure waves to detect leaks is to purposely generate transient pressure waves by closing and opening valves periodically (Mpesha et al., 2001; Elaoud et al., 2010). If a leak is present, these pressure waves are partially reflected allowing for the detection and location of the leak. Still, using pressure waves to detect leaks was reported to be unpractical for long-range pipelines (El-Shiekh, 2010).

5.4. Pressure Point Analysis

Pressure Point Analysis (PPA^{TM}) is a fast leak detection technique based on the premise that the pressure inside the pipeline drops if a leak occurs (Farmer et al., 1989, 1991). This technique requires continuous measurements of the pressure in different points along the pipeline. Using statistical analysis of these measurements, the presence of a leak is declared when the mean value of the pressure measurements decreases under a predefined threshold. The patent (Farmer, 1989) for this leak detection method is held by EFA Technologies Inc. which offers PPA^{TM}(EFA Technologies Inc., 2011b) as part of their LEAKNET^{TM}leak detection system along with MassPack^{TM}. PPA^{TM}was proven to work in underwater and cold (arctic) environments (Scott and Barrufet, 2003) and can detect leak rates less than 0.1% of flow but it is not a reliable leak detection technique during transient flow.

5.5. *Statistical*

A simpler way of detecting gas leaks, without the need of a mathematical model, is by using statistical analysis. This analysis is done on measured parameters like pressure and flow at multiple locations along the pipeline. The system generates a leak alarm only if it encounters certain patterns consisting of relative changes in pressure and flow (Zhang, 1993).

The leak thresholds are set after a tuning period during which the parameter variance is analyzed under different operating states in the absence of a leak. This tuning process needs to be done over a long period of time and is required in order to reduce false alarms (Zhang and Di Mauro, 1998). If a leak is present in the system during the tuning period, it will affect the initial data collected and the system behavior will be considered as normal. This leak would not be detected unless it would grow in size enough to go beyond the threshold.

Detection of 0.5% leaks was reported (Zhang and Di Mauro, 1998) but it is possible to detect even smaller leaks when using instruments with greater resolution. Statistical methods can also estimate the leak location. The technique is also easy to use, robust and easy to adapt to different pipeline configurations. Some of the main disadvantages of using this approach are the difficulty in estimating leak volume and high costs.

5.6. *Digital Signal Processing*

Another way to detect leaks by using measurements of the flow, pressure or other pipe parameters is to use digital signal processing (USDT, 2007). During the set-up phase, the response given by the system to a known change in flow is measured. This measurement is used together with digital signal processing to detect changes in the system response. Digital signal processing allows for the leak response to be recognized from noisy data. This kind of leak detection technique was first proposed for liquid pipelines (Golby and Woodward, 1999) but its applicability to gas pipes was also considered. Solutions for both liquid and gas pipelines are currently available (e.g. the ClampOn DSP Leak Monitor (ClampOn AS, 2011)).

This method does not need a mathematical model of the pipeline, its main purpose being that of extracting leak information from noisy data. Like the statistical approach, if during the set-up phase a leak is already present in the system it will never be detected unless its size would grow considerably. Furthermore, besides having a high cost, this leak detection technique is difficult to implement, retrofit and test.

6. Compared performance analysis

The performance level of a leak detection system can be established by a series of factors. Some of the criteria that are usually used to evaluate the performance of leak detection systems are (Stafford and Williams, 1996): the ability to determine the location of the leak, the detection speed and the ability to estimate the size of the leak. In Table 1 we summarized the most important features offered by each studied detection technique including also these criteria. The following abbreviations were used for filling this table: yes (Y), no (N), slow (S), medium (M), fast (F), low (L) and high (H). A dash was entered where a certain feature did not apply.

In what regards the leak localization capability, only techniques based on mass/volume balance and pressure point analysis lack this ability. The localization precision also differs from method to another. Some can pinpoint the location of a leak with great precision while others such as the software based methods can only give an estimated location. In these cases, other methods such as line patrolling need to be employed to find the exact leak location.

For evaluating the detection speed, we considered systems with detection times up to several minutes as fast, systems that need up to several hours as medium speed and systems with even longer detection times as slow. As expected, detection methods that employ line patrolling have the longest detection time. Optical methods have a medium detection speed when the devices are mounted on aircrafts since long distances can be covered faster. When optical detectors are used by ground patrols the detection time increases significantly but this approach is seldom utilized. All other methods can detect leaks in real time or in a matter of minutes after the leak has occurred.

Table 1: Compared common features of leak detection methods

Features	Method																				
	Visual inspection	Soap screening	Acoustic	LIDAR	Diode Laser Absorption	Millimeter Wave Radar	Backscatter Imaging	Broad Band Absorption	Fiber Optic Cable	Thermal Imaging	Multi-Spectral Imaging	Gas Filter Correlation Radiometry	Cable Sensor	Soil Monitoring	Vapor Sampling	Ultrasonic Flow Meters	Mass/Volume Balance	Real Time Transient Modeling	Negative Pressure Wave	Pressure Point Analysis	Statistical	Digital Signal Processing
Cost	L	L	H	H	M	H	H	L	H	H	H	M	H	H	H	H	L	H	L	L	H	H
Detection speed	S	S	F	M	M	M	M	M	F	M	M	M	F	S	F	F	F	F	F	F	F	F
Easy retrofitting	-	-	Y	-	-	-	-	-	N	-	-	-	N	N	N	N	Y	Y	Y	Y	Y	N
Easy usage	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y
Leak localization	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	N	Y	Y
Leak size estimation	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	Y	N	Y	Y	Y	N	Y	N

Leak size estimation is available in most detection systems. Cable sensor, soil monitoring, ultrasonic flow meters, pressure point analysis and digital signal processing do not have this ability.

Sensitivity is also an important factor in assessing the performance of a leak detection system. However, it is not an easy task to make a comparison of all techniques from the sensitivity point of view since the reported values are not always quantified using the same approach. For instance, the sensitivity of computational methods is usually presented as a percentage of nominal pipeline flow or as the minimum detectable leak flow rate while other systems report a concentration based sensitivity regardless of the pipeline flow rate. Software based methods have reported sensitivities ranging from 0.1%, in the case of pressure point analysis, to 1%, when using mass/volume balance or digital signal processing. Hardware based methods generally perform better in regards to sensitivity (USDT, 2007). For example, a vapor sampling system like LEOS (Bryce et al., 2002) can detect 0.05% leaks and most optical methods can detect gas concentrations in the ppm range.

7. Conclusions

A wide variety of leak detecting techniques is available for gas pipelines. Some techniques have been improved since their first proposal and some new ones were designed as a result of advances in sensor manufacturing and computing power. However, each detection method comes with its advantages and disadvantages.

Leak detection techniques in each category share some advantages and disadvantages. For example, all external techniques which involve detection done from outside the pipeline by visual observation or portable detectors are able to detect very small leaks and the leak location, but the detection time is very long. Methods based on the mathematical model of the pipe have good results at high flow rates while at low flow rates a mass balance based detection system would be more suitable. If we consider the costs involved by the use of each detection system, the summary in Table 1 shows that most of the available techniques are expensive. This disadvantage is prone to disappear for some of these techniques due to forthcoming technological advancements.

Combining several leak detection systems is a common practice and also a recommendation (Turkowski et al., 2007; El-Shiekh, 2010) in order to cope with the presented disadvantages. Hybrid systems benefiting from the real-time detection capability of a software based method and the high localization accuracy of a hardware based technique, along with other specific advantages of both approaches, seem to be the future trend in gas leak detection. Selecting from the wide variety of commercial solutions available is ultimately an action that has to be taken after assessing the needs of the system in which gas leak detection is needed.

Acknowledgments

This work was supported by the CNCSIS-UEFISCDI project number PN II-IDEI 940/2008.

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